

Young Massive Clusters in the Galactic Center

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Abstract. The three young clusters in the Galactic Center represent the closest examples of massive starbursts and they define the upper mass limit of the Galactic cluster mass functions. In this review, I describe the characteristics and content of the Arches, Quintuplet, and Central clusters. They each are more massive than any other cluster in the Galaxy, and the Arches cluster, in particular, has a mass and age that make it ideal for studies of massive stellar evolution and dense stellar systems. A preliminary measurement indicates that the initial mass function in the Galactic center is top-heavy, suggesting an environmental effect that has otherwise been absent in similar observations for Galactic clusters. Given the relatively more evolved nature of the Quintuplet and Central clusters, these clusters contain stars in a wide range of evolutionary states, including Luminous Blue Variables and Wolf-Rayet stars. The Quintuplet cluster provides a particularly interesting view of the most massive stars that are known, the Pistol Star and FMM362. An analysis of the mass spectrum in the Arches cluster suggests an upper mass cutoff of $\sim 150\text{--}200 M_{\odot}$.

1. Introduction

The three young stellar clusters in the Galactic Center are each individually more massive than any other in the Galaxy. As such, they represent fertile grounds for exploring a wide variety of astrophysical processes over a range of size scales. They have enough members to provide good statistics for the high mass range of the initial mass function ($10 M_{\odot} < M_{\text{initial}} < 120 M_{\odot}$). They also have coeval populations with enough mass to populate bins in the initial mass function (IMF) beyond $150 M_{\odot}$, a unique property for clusters in the Galaxy. They have more massive stars than any other Galactic cluster, allowing one to perform comparative evolution studies with the assurance that the test points are all of the same age. Given their ages, the clusters likely contain stars at all stages of evolution, from the pre-main sequence through end states, including the Luminous Blue Variable (LBV) and Wolf-Rayet (WR) stages. In addition, their unique locale allows one to infer how the initial mass function might be affected by environmental parameters, i.e. cloud temperature.

Because of their high mass, and apparent top-heavy IMF, the Galactic Center clusters contain some of the most massive stars in the Galaxy. This is important, as massive stars are key ingredients and probes of astrophysical phenomena on all size and distance scales, from individual star formation sites, such as Orion, to the early Universe during the age of reionization when the first stars were born. As ingredients, they control the dynamical and chemical evolution of their local environs and individual galaxies through their influence on the energetics and composition of the interstellar medium. They likely play

an important role in the early evolution of the first galaxies, and there is evidence that they are the progenitors of the most energetic explosions in the Universe, seen as gamma ray bursts. As probes, they define the upper limits of the star formation process and their presence likely ends further formation of nearby lower mass stars. They are also prominent output products of galactic mergers, starburst galaxies, and active galactic nuclei.

Despite the importance of massive stars, there is no known firm upper limit to the maximum stellar mass. Such a basic quantity escapes both theory, because of the complex interplay between radiation pressure and opacity, and observation, because of incompleteness in surveying the Galaxy along the plane. The Galactic Center is likely to contain the most massive star known in the Galaxy, from a statistical perspective, and it does contain several particularly good candidates.

In this review, I discuss the properties of the Galactic Center clusters and their massive stellar content.

2. Properties of the Clusters

Properties of the clusters have been reviewed in Figer et al. (1999a) and Figer (2003), and references therein, and they are summarized in Table 1.

Table 1. Properties of massive clusters in the Galactic Center^a

Cluster	Log(M1) M_{\odot}	Log(M2) M_{\odot}	Radius pc	Log($\rho 1$) $M_{\odot} \text{ pc}^{-3}$	Log($\rho 2$) $M_{\odot} \text{ pc}^{-3}$	Age <i>Myr</i>	Log(L) L_{\odot}	Log(Q) s^{-1}
Quintuplet	3.0	3.8	1.0	2.4	3.2	3–6	7.5	50.9
Arches ^b	4.1	4.1	0.19	5.6	5.6	2–3	8.0	51.0
Center ^c	3.0	4.0	0.23	4.6	5.6	3–7	7.3	50.5

^a “M1” is the total cluster mass in observed stars. “M2” is the total cluster mass in all stars extrapolated down to a lower-mass cutoff of $1 M_{\odot}$, assuming a Salpeter IMF slope and an upper mass cutoff of $120 M_{\odot}$ (unless otherwise noted). “Radius” gives the average projected separation from the centroid position. “ $\rho 1$ ” is M1 divided by the volume. “ $\rho 2$ ” is M2 divided by the volume. In either case, this is probably closer to the central density than the average density because the mass is for the whole cluster while the radius is the average projected radius. “Age” is the assumed age for the cluster. “Luminosity” gives the total measured luminosity for observed stars. “Q” is the estimated Lyman continuum flux emitted by the cluster.

^b Mass estimates have been made based upon the number of stars having $M_{\text{initial}} > 20 M_{\odot}$ given in Figer et al. (1999b) and the mass function slope in (Stolte 2003). The age, luminosity and ionizing flux are from Figer et al. (2002).

^c Krabbe et al. (1995). The mass, “M2” has been estimated by assuming that a total $10^{3.5}$ stars have been formed. The age spans a range covering an initial starburst, followed by an exponential decay in the star formation rate.

The three clusters are similar in most respects. They each contain $\sim 10^4 M_{\odot}$ in stars. The new mass estimate for the Arches cluster in the table uses the estimated number of stars have $M_{\text{initial}} > 20 M_{\odot}$ in the cluster, 160 (Figer et

al. 1999b), and the mass function in (Stolte 2003), which has a slope of -0.9 between $120 M_{\odot}$ and $10 M_{\odot}$, and 0 from $10 M_{\odot}$ to $2 M_{\odot}$, where the Salpeter value is -1.35 (Salpeter 1955); extending the mass function to lower masses does not add appreciable mass to the cluster. The clusters have very high densities, up to nearly $10^6 M_{\odot} \text{ pc}^{-3}$, and rival densities in most globular clusters. They have luminosities of $10^{7-8} L_{\odot}$, and are responsible for heating nearby molecular clouds. They also generate 10^{50-51} ionizing photons per second, enough to account for the nearby giant HII regions. The primary difference between the clusters is likely to be age, where the Quintuplet and Central clusters are about twice the age of the Arches cluster.

The three Galactic Center clusters define the extreme end in many parameters with respect to other young clusters in the Galaxy. They are each about a factor of two more massive than the next most massive young cluster, NGC3603. Their luminosities and ionizing fluxes are among the highest in the Galaxy, although both quantities decrease with age, i.e. these quantities for the Arches cluster are a factor of two to three greater than those for the Quintuplet and Central clusters. It appears that the the Arches cluster and NGC3603 have similar ionizing fluxes, but the Arches is a factor of two or three more luminous.

Given their similar ages and stellar content, the Arches cluster is more similar to NGC3603 than to any other cluster in the Galaxy. When considering young clusters outside of the Galaxy, R136 is most similar to the Arches cluster; in this case, the former is probably a factor of two more massive than the latter. The Arches cluster is a factor of six closer to us, resulting in a potential advantage in regards to confusion; however, it is not observable at UV or visible wavelengths because of the thick column of dust between us and the cluster.

3. Properties of the Massive Stars

The Galactic Center clusters contain a rich set of extraordinarily massive stars, $\gtrsim 350$ having $M_{\text{initial}} > 20 M_{\odot}$. The most massive of these stars are in various stages of post main sequence evolution, i.e. LBV and WR stars. Table 2 gives a summary of the massive stars in the Galactic Center clusters. The number of O-stars in the case of the Quintuplet and Central clusters is estimated based upon the ages of the clusters and the number of identified post-main sequence stars.

Table 2. Massive Stars in the Galactic Center Clusters

	O	LBV	WN	WC	RSG
Quintuplet	100	2	5	11 ^a	1
Arches	160	0	$\gtrsim 6$	0	0
Center	100	$\gtrsim 1$	$\gtrsim 10$	$\gtrsim 10$	2
Total	360	$\gtrsim 3$	$\gtrsim 21$	$\gtrsim 21$	3

^aIncludes the Quintuplet Proper Members (QPMs).

3.1. Luminous Blue Variables

Luminous Blue Variables are characterized by their high luminosities ($L > 10^6 L_\odot$), high temperatures ($T > 10000$ K), and photometric variability (Humphreys & Davidson 1994). They represent relatively short phases ($\tau \sim 25000$ yr) in the post-main sequence lifetimes of massive stars inbetween the O-star and WR phases.

Figer, McLean, & Morris (1995) predict that the Pistol Star is extraordinarily massive and is surrounded by the largest circumstellar ejecta ever observed ($10 M_\odot$), compared to a few M_\odot for η Car. Further to this claim, Figer et al. (1998) estimate an initial mass of $200 M_\odot$, establishing the Pistol Star as one of the most massive known. They show that the star is single based upon their Keck speckle data and spectra; the former reveal that the star is single down to a projected distance of 110 AU (14 mas), while the latter do not show an obviously composite spectrum. Figer et al. (1999c) demonstrate that the Pistol Star is indeed the progenitor of its surrounding ejecta which still expands away from the star at 60 km s^{-1} .

Figer et al. (1999a) identify a star with spectroscopic and photometric properties similar to those of the Pistol Star, and located just a few arcminutes away, but still in the Quintuplet cluster. Geballe, Najarro, & Figer (2000) determine that this star, FMM362, is a “near twin” to the Pistol Star, having comparable luminosity, and thus mass, and variability. Yet, FMM362 is not surrounded by circumstellar ejecta, although we have recently obtained near-infrared spectra showing a drastic change in temperature with respect to earlier observations. The new spectra do not contain most of the previously observed lines, suggesting a much cooler temperature for the observed photosphere. While we do not know for sure whether this star is experiencing an eruption, the observations are suggestive of such an event. At the very least, the temperature of the star is highly variable, a characteristic of LBVs as they transition between quiescent and eruptive stages.

The presence of the Pistol Star and FMM362 in a cluster that is $\sim 4 \text{ Myr}$ old is a puzzle, given that these stars should not live much longer than $\sim 2 \text{ Myr}$ (Figer et al. 1998). Note that luminosity is linearly proportional to mass for massive stars ($M_{\text{initial}} \gtrsim 200 M_\odot$), so their lifetimes asymptotically approach 2 Myr with increasing mass (Bond, Arnett, & Carr 1984). One solution to the puzzle may be that the stars are binary/multiple, composed of lower mass stars which have longer lifetimes. Another possibility is that these stars are products of recent mergers. Indeed, Kim et al. (2000) simulate the evolution of the Arches cluster, finding that at least one high mass merger should occur in such a cluster in the first few Myr of its existence.

IRS16NE is a massive star in the central parsec that has a near-infrared spectrum similar to those of the Pistol Star and FMM362 (Tamblyn et al. 1996). Najarro et al. (1997) estimate a luminosity and temperature that place the star amongst LBVs in the HR diagram. However, the tell-tale variability, characteristic of LBVs, has not yet been observed for this star (Tamura et al. 1996). Further monitoring might yet reveal that it is indeed in the LBV stage. If it does not, then it raises the question of how a star that otherwise appears to be similar to LBVs can resist the instabilities in such stars.

See Paumard, Maillard, Morris, & Rigaut (2001) for two other potential LBV stars in the central parsec, IRS34W and IRS16C.

3.2. Wolf-Rayet stars

All three clusters each contain more WR stars than in other other Galactic cluster. Taken together, the three clusters contain 10-15% of all WR stars in the Galaxy. The Central cluster contains approximately 20 WR stars, with a roughly equal distribution of WC and WN types (Krabbe et al. 1995; Blum, Sellgren, & Depoy 1995; Tamblyn et al. 1996; Genzel et al. 2003). The Arches cluster contains at least half a dozen WNL types (Nagata et al. 1995; Figer 1995; Cotera 1995; Cotera et al. 1996; Blum et al. 2001; Figer et al. 2002), but it contains no WC stars. This is consistent with its age of ~ 2.5 Myr (Figer et al. 2002), and the models in Meynet (1995). The Quintuplet cluster contains at least a dozen WR stars, with an equal split between WN and WC types, excluding the Quintuplet Proper Members (Figer, McLean, & Morris 1995; Figer et al. 1999a; Homeier et al. 2003).

3.3. The Quintuplet-proper Members (QPMs)

The Quintuplet-proper members (QPMs) are the five very red sources for which the cluster was named (Nagata et al. 1990; Glass, Moneti, & Moorwood 1990; Okuda et al. 1990). They are very bright, $m_K \approx 6$ to 9, and have infrared color temperatures between ≈ 600 to 1,000 K. After dereddening, their integrated infrared luminosities are in the range $10^{4.3}$ to $10^{5.2} L_\odot$. Oddly, the objects are spectroscopically featureless at all wavelengths observed, making their spectral classification ambiguous.

Figer, Morris, & McLean (1996) and Figer et al. (1999a) argue that these objects are not protostars, OH/IR stars, or OB stars still embedded in their natal dust cocoons. Instead, they argue that these stars are dust-enshrouded WCL stars (DWCLs), similar to other dusty Galactic WC stars (Williams, van der Hucht, & The 1987), i.e. WR 140 (Monnier, Tuthill, & Danchi 2002) and WR 98A (Monnier, Tuthill, & Danchi 1999). Moneti et al. (2001) favor this hypothesis as a result of their analysis of ISO spectroscopy of the sources. New evidence in support of this hypothesis comes in the form of the identification of a carbon feature near $6.2 \mu\text{m}$ in the QPMs' spectra (Chiar et al. 2003), a detection at x-ray wavelengths (Law & Yusef-Zadeh 2003), and a detection at radio wavelengths (Lang et al. 2003).

If they are DWCLs, then they are dustier than any others, begging the question: Is there something special about the Galactic Center environment, such as its metallicity, which causes the winds of DWCLs to be particularly dusty? If they are not DWCLs, then they represent a new phenomenon. The same logic applies to the mid-infrared sources in the Central Cluster (Becklin, Matthews, Neugebauer, & Willner 1978). Eisenhauer et al. (2003) show that some of the mid-infrared sources in the central parsec are indeed DWCLs.

4. The Slope of the IMF in the Arches cluster

Morris (1993) argues that star formation in the Galactic center could favor high mass stars as a result of environmental conditions, i.e. strong tidal forces,

enhanced cloud turbulence and gas heating, and strong magnetic fields. The presumably high metallicity in the Galactic center might also produce a variation in the spectrum of masses formed there with respect to what is observed in the disk of the Galaxy, but it is still not clear if the metallicity in the Galactic center is extrasolar (Ramírez et al. 2000).

Figer et al. (1999b) use HST/NICMOS data to estimate a mass function slope of -0.7 for the Arches cluster, over a mass range of $6 M_{\odot}$ to $120 M_{\odot}$, where the Salpeter value is -1.35 (Salpeter 1955). They were unable to estimate a slope for the Quintuplet cluster, given the degeneracy in the mass-magnitude relationship for cluster older than $4 Myr$. The same problem exists for the Central cluster. Stolte et al. (2002) further refine the estimate for the slope of the mass function for the Arches cluster, finding a value of -0.8 , over a mass range of $6 M_{\odot}$ to $65 M_{\odot}$. The slightly steeper slope with respect to the value in Figer et al. (1999b) is due to a proper treatment of differential extinction across the field of the cluster. Both groups note that significant mass segregation causes a much shallower slope, roughly zero, toward the center of the cluster.

Kim et al. (2000) use N-body simulations of the cluster to determine that the present distribution of stars in the cluster is consistent with an IMF having a slope of -0.75 . Portegies Zwart, Makino, McMillan, & Hut (2002) argue that the present-day mass function is consistent with an IMF that is similar to the Salpeter value; however, their analysis requires a cluster mass of $4(10^4) M_{\odot}$, or a factor of four above the observed value.

5. An Upper Mass Cutoff to the IMF in the Arches cluster

Figer (2003) argue that there is evidence of a firm upper mass cutoff to the IMF in the Arches cluster. Assuming an IMF slope of -0.9 (see above), we should expect to see much more massive stars than are currently observed. We should expect at least 10 (4) stars more massive than $M_{\text{initial}}=300 M_{\odot}$, and about 30 (11) more massive than $M_{\text{initial}}=150 M_{\odot}$ (the numbers in parentheses are for a Salpeter IMF slope). Indeed, we should even expect one star with an initial mass of $1,000 M_{\odot}$! Yet, we see no stars in the Arches cluster that are more massive than $M_{\text{initial}}=150 M_{\odot}$. This apparent deficit might partially be explained by the short lifetimes of such massive stars. They only live for about $2 Myr$, according to Bond, Arnett, & Carr (1984); whereas, the Arches cluster is about $2.5 \pm 0.5 Myr$ old (Figer et al. 2002).

Weidner & Kroupa (2004) recently claim a fundamental upper mass cutoff from their analysis of the mass distribution in R136 in the LMC. They find a cutoff of $\sim 150 M_{\odot}$, similar to the implied value for the Arches cluster.

6. Conclusions

The Galactic center clusters are unique in the Galaxy, providing for a large range of studies regarding cluster formation, massive stellar formation and evolution, and feedback mechanisms, to name a few. Given their masses and relative youth, the clusters contain a large fraction of the massive stars in the Galaxy. Initial estimates indicate that the IMF in the Galactic center is skewed toward massive stars. Further, the clusters suggest that there is a firm upper limit to the most

massive star that can form near $\sim 150\text{--}200 M_{\odot}$. If these measurements remain valid, then the IMF is not universal, and there is an upper limit to the maximum mass of a star.

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